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Active tectonics of the Ganzi–Yushu fault in the southeastern Tibetan Plateau

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ABSTRACT

The ongoing convergence between India and Eurasia apparently is accommodated not merely by crustal shortening in Tibet, instead also by motions along strike slip faults which are usually boundaries between tectonic blocks, especially in the Tibetan Plateau. Quantification of this strike slip faulting is fundamental for understanding the collision between India and Eurasia. Here, we use a variety of geomorphic observations to place constraints on the late Quaternary kinematics and slip rates of the Ganzi–Yushu fault, one of the significant strike-slip faults in eastern Tibet. The Ganzi–Yushu fault is an active, dominantly left-lateral strike-slip structure that can be traced continuously for up to 500 km along the northern boundary of the clockwise-rotating southeastern block of the Tibetan Plateau. We analyse geomorphic evidence for deformation, and calculate the late Quaternary slip rates at four sites along the eastern portion of the fault trace. The latest Quaternary apparent throw rates are variable along strike but are typically ~1 mm/a. Rates of strike-slip displacement are likely to be an order of magnitude higher, 8–11 mm/a. Trenching at two locations suggests that the active fault behaviour is dominated by strike-slip faulting and reveals several earthquake events with refined information of timing. The 2010 M_w 6.9 Yushu earthquake, which occurred on the northwestern segment of the Ganzi–Yushu fault zone, provides additional evidence for fault activity. These observations agree with GPS-derived estimates, and show that late Quaternary slip rates on the Ganzi–Yushu fault are comparable to those on other major active strike-slip faults in the eastern Tibetan Plateau.

1. Introduction

The ongoing convergence between India and Eurasia apparently is accommodated not merely by crustal shortening in Tibet, instead also by motions along strike slip faults which are usually boundaries between tectonic blocks, especially in the Tibetan Plateau (Molnar and Tapponnier, 1978). To explain this deformation, two influential end-member views of continental deformation have been debated during the last several decades: (1) block models, in which intracontinental deformation can be concentrated on major faults separating a number of relatively rigid blocks (e.g., Dewey et al., 1973; Avouac and Tapponnier, 1993; Peltzer and Saucier, 1996; Tapponnier et al., 2001; Meade, 2007; Thatcher, 2007); or (2) continuum models, in which deformation is regionally distributed in the shallow brittle crust, and is essentially continuous at depth (e.g., Molnar and Tapponnier, 1975; England and McKenzie, 1982; England and Houseman, 1986). When the two views are applied to eastern Asia, large slip rates on major faults are required by block models, but not by continuum models. Thus, documentation and quantification of kinematics and slip rates on the major strike slip faults, along with observations of historical earthquake activity, are fundamental for understanding the collision between India and Eurasia.

The four major earthquakes ($M_w > 7.0$) which occurred in the Tibetan Plateau during the last two decades (1997 M_w 7.5 Manni earthquake (Xu, 2000), 2001 M_w 7.8 Kunlunshan earthquake (Xu et al., 2002), 2008 M_w 7.2 Yutian earthquake (Xu et al., 2011) and 2008 M_w 7.9 Wenchuan earthquake (Xu et al., 2009)), and the 2010 M_w 6.9 Yushu earthquake, all occurred around the boundaries of the Bayan Har fault-block (Fig. 1), also known as the Songpan block (Thatcher, 2007) or Kunlun block (Gan et al., 2007), surrounded by Longmenshan Fault (east boundary), Xianshuihe Faunt and Ganzi–Yushu fault (south boundary), and Kunlun fault (north boundary). The published GPS velocities (e.g. Wang et al., 2001; Gan et al., 2007; Thatcher, 2007) suggest the southward movement of the Bayan Har fault-block relative to stable Eurasia, but the mechanisms and starting time of this movement have been a matter of debate (Chen et al., 1994; Kirby et al., 2000, 2002, 2003; Clark et al., 2005). The eastern boundary faults of the block accommodated significant crustal shortening during the Late Triassic Indosinian Orogeny (Chen and Wilson, 1996; Li et al., 2003), and the Longmenshan region at the eastern margin of the block has been identified as a major thrust zone that was reactivated in the India–Asia collision (e.g., Avouac and Tapponnier, 1993; Xu and Kamp,

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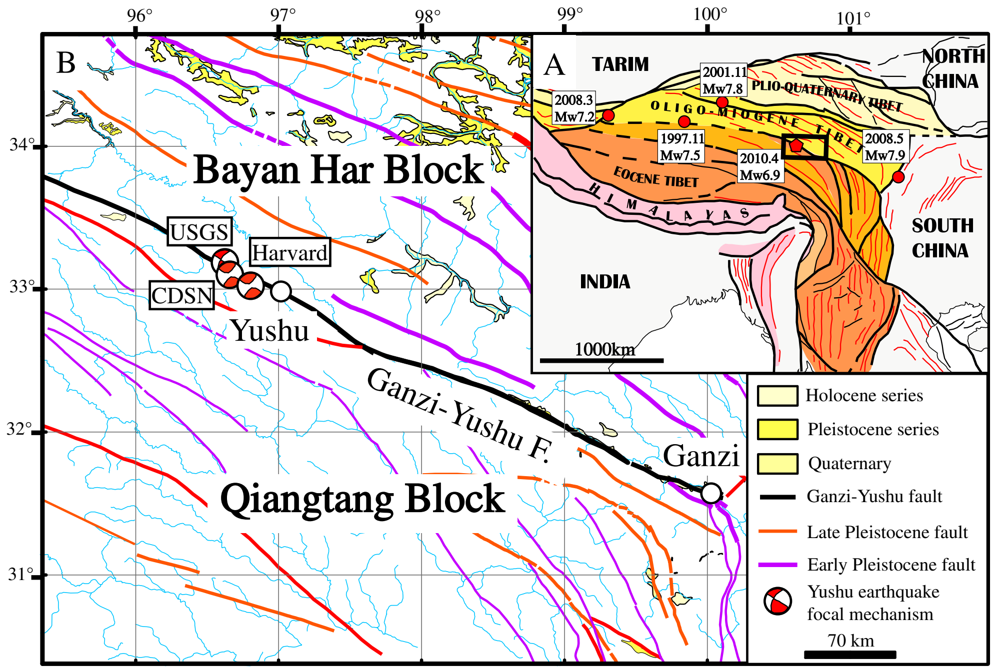

Fig. 1. Regional seismotectonics and historical earthquakes of the study region. A, Simplified map of major tectonic boundaries and Tertiary faults in Tibet (after Tapponnier et al., 2001). Bold black lines are major faults and localized shear zones (megathrust or strike-slip) with largest finite offsets, dashed where uncertain. Thin red lines are crustal thrusts. Red circles are the four largest earthquakes ($M_w > 7.0$) during the last two decades in Tibet. Pentagram is the 2010 M_w 6.9 Yushu earthquake. The black rectangle indicates the location of panel B. B, faults, major river systems, and areas of Quaternary deposition in the east-central Tibetan Plateau. The fault locations are modified from Deng (2007).The 2010 Yushu earthquake focal mechanism was extracted from the CDSN (Chen, 2010), USGS and Harvard (USGS, 2010) catalogues.

2000). The northern and southern boundaries of the block are major left-lateral strike-slip faults – the Ganzi–Yushu and Xianshuihe fault system to the south, and the Kunlun fault system to the north.

In order to understand the mechanism of the Bayan Har fault-block in the India–Asia collision, the late Cenozoic activity and kinematics of the major faults along the block margins must be documented. Much work about the late Cenozoic activity and kinematics of faults in the Longmenshan has been done by Chen et al. (1994), Burchfiel et al. (1995) and Densmore et al. (2007). The slip rates of the Xianshuihe and Kunlun faults have been well constrained (e.g. Allen et al., 1991; Van der Woerd et al., 2002), there are also many results of slip rate on Ganzi–Yushu fault from fieldwork (Zhou et al., 1996; Wen et al., 2003; Peng et al., 2006) and GPS (Wang et al., 2001; Shen et al., 2005; Gan et al., 2007; Wang, 2009). Tapponnier et al. (2001) inferred fast rates, about 15 mm/a, to argue for rigid-block extrusion, but others (e.g., England and Molnar, 2005) have suggested that slow rates, about 5 mm/a or slower, are consistent with continuous deformation. The kinematics of the Ganzi–Yushu fault, its slip rate, and the timing of paleoearthquakes on the fault all remain poorly constrained. Some slip rates have been obtained from terrace or alluvial fan offsets along with age estimates from TL (thermoluminescence) dating (Zhou et al., 1996; Wen et al., 2003). There has also been some work using river offsets, although the ages of these offsets were only loosely constrained as Holocene (Peng et al., 2006). The huge range of the slip rates, which is from 3 mm/a to 13 mm/a, couldn't test different deformation models. The reasons of the huge range come from two aspects, one is the dating method and another is the choice of offset markers. Moreover, because of the high altitude and remoteness of the fault, there has been very little work on paleoearthquakes in these areas.

We address the fault trace by presenting geomorphic evidence for deformation along the Ganzi–Yushu fault, and constrain the fault behaviour by paleoseismology. We use a combination of techniques, including field mapping, image interpretation, surveying of offset geomorphic markers, and trenching, in order to examine the history of fault slip over the last few thousand years.

2. Geological setting

The Ganzi–Yushu fault zone forms part of the boundary between the Qiangtang and Bayan Har blocks in the eastern Tibetan Plateau (Zhang et al., 2003; He et al., 2006). The Ganzi–Yushu fault zone can be traced for ~500 km along strike and consists of a series of generally NW-striking fault segments. The western most tip of the fault zone occurs near Qutang township, in Zhiduo county of Qinghai Province, and the fault extends eastward through Dangjiang, Yushu, Dengke, and Yulong townships to end at Ganzi county in Sichuan Province. Where it is visible at the surface, the fault appears to dip 70–85°NE near the surface, except for a SW-dipping segment near Tuodang township (Li et al., 1995). The 2010 M_w 6.9 Yushu earthquake ruptured the Ganzi–Yushu fault over a total distance of about 50 km (Chen et al., 2010; Li et al., 2012). Focal mechanism solutions (Chen, 2010; USGS, 2010) and displaced geomorphic features indicate that the earthquake rupture is nearly pure left-lateral strike-slip with a minor SW dip-slip component.

Exposures of the active Ganzi–Yushu fault show that it coincides with zones of dense fracturing in pre-Quaternary bedrock; the width of these zones is generally ~10–50 m but is rarely up to a few hundred meters (Zhou et al., 1996). In remote sensing imagery, strands of the fault form clear linear features associated with scarps, shutter ridges, and offset drainages characteristic of active strike-slip deformation (Zhou et al., 1996). The fault movement appears to be dominated by left-lateral strike-slip, with little consistent net vertical slip (Peng et al., 2006). Previously-published estimates of strike-slip rates span a large range from 3 mm/a to 14 mm/a (Fig. 2) (Zhou et al., 1996; Wen et al., 2003; Peng et al., 2006). Many of these are based on low-resolution geomorphic markers (e.g., river offsets) and on imprecise